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Review

Contaminants reduce the richness and evenness of marine communities: A review and meta-analysis

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Contamination substantially reduces the biodiversity of marine communities in all major habitat types and across all major contaminant classes.

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ABSTRACT

Biodiversity of marine ecosystems is integral to their stability and function and is threatened by anthropogenic processes. We conducted a literature review and meta-analysis of 216 studies to understand the effects of common contaminants upon diversity in various marine communities. The most common diversity measures were species richness, the Shannon–Wiener index (H′) and Pielou evenness (J). Largest effect sizes were observed for species richness, which tended to be the most sensitive index. Pollution was associated with marine communities containing fewer species or taxa than their pristine counterparts. Marine habitats did not vary in their susceptibility to contamination, rather a ∼40% reduction in richness occurred across all habitats. No class of contaminant was associated with significantly greater impacts on diversity than any other. Survey studies identified larger effects than laboratory or field experiments. Anthropogenic contamination is strongly associated with reductions in the species richness and evenness of marine habitats.

1. Introduction

Coastal marine ecosystems are amongst the most diverse and productive on earth (e.g. de Forges et al., 2000). The rich biodiversity of these systems is integral to their proper functioning and may afford them greater stability and resilience to natural and anthropogenic perturbations (Hooper et al., 2005). However, the diversity of marine ecosystems is increasingly threatened by anthropogenic stressors including over-harvesting, habitat destruction and climate change (Vitousek et al., 1997). In the scientific literature, and in the public mind, contamination from anthropogenic sources is assumed to be an additional threat to marine biodiversity (Crowe et al., 2004). However, susceptibility to contaminants varies between species and there are mechanisms (such as species replacement) that may mask the effects of contaminants on diversity *per se* (Washington, 1984). Moreover, there are many varieties of contaminant and many different marine habitats. Review articles have tended to focus upon particular marine habitats (Glover and Smith, 2003; Legendre and Rivkin, 2002), regions (He and Morrison, 2001; Lotze and Milewski, 2004; Morrison and Delaney, 1996) or contaminants (Pastorok and Bilyard, 1985; Rabalais, 2002; Wu, 1995). Consequently our general understanding of how different contaminants influence patterns of marine biodiversity across habitats is limited (Crowe et al., 2004; Oliveira and Qi, 2003). From a management perspective, key questions remain as to which marine habitats are most vulnerable to contaminants and which classes of contaminants are most likely to cause negative impacts on diversity. Reliable information regarding these key questions will greatly assist in the prioritisation of remediation efforts.

Contaminants come in many forms and there is the potential for different toxins to impact differently upon diversity. Some contaminants (such as some metals) are essential for marine life at trace concentrations, whilst many modern and artificially synthesized compounds (e.g. "emerging contaminants") may have no biological origin or function. Other potential contaminants, such as nutrients, may be limiting in marine ecosystems and their enrichment as a result of anthropogenic activities may in fact lead to enhanced resource availability with concomitant increases in species richness (Hall et al., 2000).

Similarly there is the potential for particular marine habitats to vary in their susceptibility to contamination. Some systems are inherently more diverse than others and may have greater functional redundancy allowing for species replacement rather than

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loss. Alternatively, some habitats such as seagrass meadows may comprise communities reliant upon a few, specific foundation species (or ecosystem engineers) and hence be potentially more vulnerable to habitat collapse. Habitats also typically occur in different environments that may be subject to more or less contaminant exposure. Many contaminants accumulate in sediments and may be expected to affect sediment infauna whilst the propensity for contaminants to persist in well-flushed rocky reef environments may be relatively low. Hence there are a range of reasons why we might predict differential sensitivity of habitat types and differential impact of contaminant classes.

Contaminant impacts may also be assessed in a variety of ways and within the aquatic pollution literature there are a range of biological indices that have been developed for particular types of contamination. In order to compare across habitats and contaminants, however, it is necessary to examine impacts on diversity indices which are non-specific and designed to reflect total environmental stress (Gray and Delaney, 2008; Washington, 1984). The simplest measure of diversity is the number of species per unit area or sampling effort (species richness). However, a recognized component of diversity is "evenness" or the abundance at which each species occurs within an area (Pielou, 1975). Evenness measures may be expected to respond to changes in community composition or structure even when there is no change to absolute species richness. Many commonly used diversity indices typically include a measure of both species richness, and the evenness of species distributions. If anthropogenic contamination acts to remove rare species from the system entirely then species richness should be the most sensitive indicator of impact. If contamination changes community structure, particularly by modifying the effective dominance of key species one might expect that evenness measures will be most sensitive to anthropogenic contamination.

Here we present the results of a systematic literature review and meta-analysis in which we address five specific questions about contaminant impacts on marine biodiversity:

1) What diversity measures are most commonly used in the monitoring of contaminant impacts?
2) In which habitats are researchers typically interested in the effects of contaminants on diversity?
3) Do marine habitats vary in their susceptibility to impacts of contamination upon diversity?
4) Do specific classes of contaminant vary in their ability to impact upon marine diversity?
5) Do the results of ecological investigations depend upon the research approach used (i.e. mensurative survey studies, manipulative experiments and laboratory-based mesocosms)?

2. Methods

2.1. Search methodology

A systematic literature review was conducted to capture a representative sample of the marine pollution literature. We first used a specific list of search terms in four databases: Aquatic Sciences and Fisheries Abstracts (1971–present), Biological Abstracts (1969–2003), Current Contents (1998–present) and Web of Science (1900–present). The following search strategies were used on each database and searches were limited to English language primary studies (not reviews) published in peer-reviewed journals:

Search 1. "*pollution* AND *marine* AND (*biodiversity* OR *diversity*)"
Search 2. Results of search 1 crossed with the terms; "*hydrocarbon*, *PAH*, *metals*, *nutrient*, *sewage*, *solid waste*, *effluent*"

We read the abstracts of all of the papers that emerged in these searches ($n > 800$) and selected for review, those with a marine focus and which reported the effects of anthropogenic contamination upon the diversity of recipient communities. Studies must have measured levels of contamination. Diversity could either be studied in terms of the diversity of a community at the species level or higher taxonomic levels, or as the genetic diversity of a population of an individual species. We then examined the citation lists of papers selected in the first round in order to capture studies that had been published prior to the database selections, or that had been published in journals not indexed in the databases we searched (Hillebrand, 2002). Again, we selected articles from this group with a marine focus and which reported the effect of contamination upon biodiversity. In total 216 research articles satisfied the criteria for inclusion in the review.

From these studies we extracted qualitative background data relating to contaminant type (metals, hydrocarbons, nutrients, sewage or mixtures), habitat type (pelagic, soft sediments, seagrass meadows and intertidal, coral and subtidal reefs), and diversity measures (species richness, Shannon–Wiener, Pielou, Margalef's, Simpson's or 'other'). We then collated data on the overall finding of the research (reduced, increased or no effects on diversity) as concluded by the authors of the papers and the direction and magnitude of the change (response ratios – see details below). Some of the studies performed no formal tests of hypotheses but because they presented the effects of contamination upon marine diversity we were still able to extract the required data from these studies. Some studies identified taxa to the lowest possible level and did not necessarily report species-level diversity. However, if they reported 'species richness' then we accepted their definition of this term.

2.2. Design criteria for meta-analysis

In addition to this qualitative review, we performed a quantitative meta-analysis. We focused our meta-analysis on studies which reported the most commonly used diversity indices: species richness (S; species per unit area), the Shannon–Wiener index (H′) and Pielou evenness (J). At least one of these measures was reported in 175 papers from the initial 216 included in the literature review.

For these studies we calculated response ratios (effect sizes) attributable to pollution. We defined the response ratio as the proportional change in mean diversity from experimental controls to treatments, or between reference and impact sites in the case of observational studies (Hedges et al., 1999; Hillebrand et al., 2007). In some cases, the effect size data had to be extracted from graphs and is considered an estimate of observed effects only. Survey studies either examined species richness and evenness along gradients away from contaminant sources, or contrasted diversity at reference to potentially impacted locations. For gradient studies we calculated an effect size by contrasting diversity and evenness at the sampling location closest to the contaminant source, to reference locations furthest from the source. For designs contrasting reference and potentially impacted locations, we compared diversity at control locations to diversity at impacted locations after the onset of contamination. Field and laboratory experimental studies typically involved contrasting species richness and evenness following exposure to a range of concentrations of contaminants. For these studies we compared control communities with communities exposed to the highest level of contamination. Effect sizes were contrasted amongst marine habitats, classes of contaminants and research approaches using separate one-way analyses of variance (ANOVA).

3. Results

3.1. Community types, approaches and impacts

Of the over 800 titles and abstracts examined, a total of 216 papers fulfilled the criteria for inclusion in the review (Appendix I). The vast majority of research (~64%) was conducted in soft sediment systems (Fig. 1a). Research into hard-substrate habitats such as intertidal rock platforms and temperate and tropical subtidal reefs were comparatively rare, as were studies on pelagic vertebrate and invertebrate communities such as fish and plankton (Fig. 1a). Research predominantly took the form of field-based surveys, with field and laboratory experiments that manipulate levels of contaminants being less common (Fig. 1b). The most frequently used measures of diversity and evenness were species richness (number of species per unit area), the Shannon–Wiener index (H′) and Pielou evenness (J; Fig. 1c). Margalef's richness (Dm) and Simpson's diversity (D) were also used occasionally (Fig. 1c).

In each habitat type the vast majority of published reports concluded that there were significant negative effects of pollution upon species richness (Fig. 2b). Similarly, all contaminant types were associated with negative effects upon species richness (Fig. 2a). Occasional increases in species richness were associated with pollution (Fig. 2a). Without exception, increases in diversity were correlated with exposure to nutrient enrichment in various forms (eutrophication, sewage, hydrocarbons, or mixtures of